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# Tillage Effects on Surface Soil Physical Conditions and Sorghum Emergence

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## ABSTRACT

**Tillage and soil crusts, among other factors, influence seedling emergence. Crust strength (CS) is related to crust water content (WC), which is influenced by tillage. Tillage also influences surface soil physical conditions that may be related to CS. This study tested the hypothesis that different tillage methods result in different CS at similar times after rainfall or irrigation and determined which tillage-mediated soil factors were responsible for CS differences of Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustolls). Tillage treatments during fallow from winter wheat (*Triticum aestivum* L.) harvest to grain sorghum [*Sorghum bicolor* (L.) Moench] planting were moldboard (MT), disk (DT), rotary (RT), sweep (ST) and no-tillage (NT). Initial tillage usually caused the greatest differences in surface conditions. Subsequent tillage and weathering eliminated most differences by sorghum planting time. Moldboard tillage, which covered most residues, usually had the greatest effect and NT, which maintained surface residues, usually had the least effect on surface conditions. Conditions evaluated were organic matter content, dry aggregate size, modulus of rupture of briquettes, crushing resistance of briquette fragments, random roughness, surface residues, and crust strength and water content. Sprinkler irrigations after sorghum planting did not result in crusts that impeded seedling emergence, but more intense rain may have caused problems. Because surface conditions generally improved with time after initial tillage, results of this study suggest that major tillage, where used, should be performed well before planting to minimize plant establishment problems. Adverse surface conditions can be minimized by using a conservation tillage system, such as NT.**

***Additional Index Words:*** **residue management, soil organic matter, soil aggregates, soil crusts, conservation tillage, no-tillage.**

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SEEDLING EMERGENCE problems result from such factors as high crust strength, high water and low oxygen content in the seed-zone, and low soil temperature. Crusts result from precipitation or irrigation on soils with low-stability surface aggregates. Depending on soil water content (WC), temperature, and crust thickness and strength, crusts may reduce emergence rate or plant populations (Hanks, 1960; Hudspeth and Taylor, 1961; Parker and Taylor, 1965; Taylor, 1962; Taylor et al., 1966; Wanjura, 1973). To avoid replanting, many producers attempt to break the crusts, but this results in additional production expenses and may not be successful. Crust WC influences crust strength (CS) (Hanks, 1960) and tillage methods influence soil WC, especially when tillage influences surface residue levels (Unger, 1978; Unger et al., 1971; Unger and Wiese, 1979). Tillage also influences surface soil physical conditions other than WC. It was, therefore, hypothesized that different tillage methods would result in different CS at similar times after precipitation or irrigation. This study tested this hypothesis and determined which tillage-mediated soil factors were responsible for the CS differences.

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## MATERIALS AND METHODS

### General Details, Treatments, and Crop Management

The study was conducted at the USDA Conservation and Production Research Laboratory, Bushland, TX, on a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustolls) with 0.3% slope. Morphologically, Pullman soils exhibit a high degree of uniformity within a given locale. There is, however, some variation across the region of occurrence, which encompasses about 1.5 million ha (Unger and Pringle, 1981). The soil is very slowly permeable, mainly because of a dense silty clay B22t horizon at the 0.41- to 0.74-m depth, which contains large amounts of montmorillonitic clay. The Ap horizon (0- to 0.15-m depth) has < 20% water-stable aggregates (Unger, 1969), which results in major dispersion and surface sealing following precipitation or irrigation; contains about 17, 53, and 30% of sand, silty, and clay, respectively; and has a bulk density of about 1.4 $Mg/m^3$ when not loosened by recent tillage.

The surface conditions were evaluated from harvest of irrigated winter wheat (*Triticum aestivum* L.) to emergence of grain sorghum [*Sorghum bicolor* (L.) Moench] in a 3-yr wheat-sorghum-sunflower (*Helianthus annuus* L.) rotation. Three cycles of the rotation were completed on separate adjacent areas starting with the 1977–78 wheat crop and ending with wheat harvest in 1983. Approximate dates of performing operations and the periods involved are given in Table 1. The fallow periods started after wheat harvest around 1 July. The effects of tillage methods on water conservation and use, and on crop yields are reported elsewhere (Unger, 1984).

Wheat that preceded fallow was planted on furrow-irrigated land and uniformly managed for relatively high yields on the entire plot area. Furrow spacing was 1 m and drill row spacing was 0.25 m.

After wheat harvest, plots were established for two residue levels and five tillage treatments. Tillage plots were 8-m wide and residue-level subplots were 4-m wide. All were 120-m long. The study had a randomized block, split plot design with three replicates. Residue-level treatments consisted of no removal of residues and removal of standing residues before imposing the tillage treatments. Residues were removed with a flail-type forage harvester operated about 30 to 50 mm above the soil ridges. The harvested residues were collected and weighed.

Tillage treatments were moldboard (MT), disk (DT), ro-

**Table 1—Months and years in which operations were performed or fallow periods occurred in wheat-grain sorghum-sunflower crop rotation at Bushland, TX.**

| | Crop area | | |
|---|---|---|---|
| Operation or period | 1 | 2 | 3 |
| Harvest initial wheat | July 78 | July 79 | July 80 |
| Fallow (wheat to sorghum) | July 78–June 79 | July 79–June 80 | July 80–July 81 |
| Plant sorghum | June 79 | June 80 | June 81 |
| Harvest sorghum | Sept. 79 | Oct. 80 | Oct. 81 |
| Fallow (sorghum to sunflower) | Sept. 79–June 80 | Oct. 80–June 81 | Nov. 81–June 82 |
| Plant sunflower | June 80 | June 81 | June 82 |
| Harvest sunflower | Aug. 80 | Sept. 81 | Aug. 82 |
| Plant wheat | Oct. 80 | Oct. 81 | Sept. 82 |
| Harvest final wheat | July 81 | July 82 | July 83 |

tary (RT), sweep (ST), and no-tillage (NT). Moldboard and RT were performed once after each wheat harvest, then DT and ST, respectively, were used as needed for weed control. On DT and ST plots, these operations were repeated as needed for weed control. Initial and secondary tillage depths were about 0.15 and 0.10 m, respectively. Weeds on NT plots were controlled with atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-triazine)] and 2,4-D [(2,4-dichlorophenoxy) acetic acid] applied soon after wheat harvest at rates of 0.34 and 0.11 g/m$^2$, respectively. Terbutryn [2-(*tert*-butylamino)-4-(ethylamino)-6-(methylthio)-*s*-triazine][3] was applied at a 0.34-g/m$^2$ rate to all plots for weed control during the sorghum growing season. Terbutryn was incorporated with a rolling cultivator on all except the NT plots. The rolling cultivator also formed 1-m-spaced ridges and furrows on all except the NT plots. On NT plots, the ridges and furrows remained intact during the fallow period.

Sorghum was planted on 13, 26, and 4 June in 1979, 1980, and 1981, respectively. The sorghums were Dekalb medium-maturity hybrids 'C46+', 'C42y+', and 'DK42y' in the respective years and were planted about 38-mm deep on the ridges with unit planters having double-disk openers and depth bands. The intended population was about 96 000 plants/ha, but actual populations were higher in some cases (see Seedling Emergence subsection). Within 2 d after planting, plots were sprinkler irrigated at about 27- and 47-mm water application per hour in 1979 and 1980, respectively, in an attempt to induce crusting that might cause differential seedling emergence among treatments. Equipment problems precluded irrigation in 1981. The amount of water applied was determined from one 49-mm diam collector in each plot. Water applied averaged 35 mm.

Precipitation amount and intensity were measured at the experimental site with standard and recording rain gauges, respectively. Intensities were calculated only for rainstorms that caused major soil dispersion and after which CS were determined.

The plots were not tilled between sorghum harvest and sunflower planting. Details of management for sunflower and the subsequent wheat crop are presented elsewhere (Unger, 1984).

## Determinations and/or Observations

Details of evaluations of the wheat crop before fallow, conditions at or near the soil surface, and of sorghum emergence are given in Table 2. Additional information follows.

Wheat grain yields were determined by harvesting the entire area with a field combine harvester. Before harvesting for grain, the entire plants were clipped near the soil surface from two 1-m by 1-m areas per plot. These samples were air dried, then threshed to determine the initial amounts of residue per plot. Surface residues in the field after tillage were compared with standard pictures to estimate the amount present (Duley, 1958).

About 5 to 8 kg of surface soil was used per sample for determining dry aggregate size distribution. The samples were oven-dried at 50°C before analysis with a rotary apparatus having sieves with 0.42-, 0.84-, 2.0-, 6.4-, and 18.3-mm square openings (Chepil, 1962).

Bulk samples of soil were collected before and after each tillage operation. Loose residues were not included in the samples. The soil was air dried before grinding, then used for determining organic matter (OM) content (Jackson, 1958), modulus of rupture (MR) (Richards, 1953), and crushing resistance (CR) of briquette fragments. For MR, the Shell Mode Transverse accessory of a Model 405 Universal Sand Strength Machine (Harry W. Dietert Co., Detroit, MI)[4] was used to break the briquettes that were dried at 50°C in a forced-draft oven. After determining MR, the CR of briquette fragments was determined with a 4.76-mm-diam flat-point penetrometer (Model 719-5MRP, John Chatillon & Sons, Kew Garden, NY 11415)[4] as the fragments lay flat on blotter paper.

Crust strengths were measured in the field as the soil surface dried after significant rainstorms. Ten measurements were made at each of two sites per subplot with the same or a similar penetrometer as used for measuring the CR. Samples for determining crust WC were obtained at the same time and site where the CS were measured.

Soil penetration (PR) resistance was measured in the field to a 0.30-m depth with hand-operated penetrometer having a 20-mm long and 12.7-mm diam conical point. These measurements were made after planting sorghum. Samples for WC determination were obtained to the same depth and at the sites where PR measurements were made.

Surface random roughness (RR) (Allmaras et al., 1966) was evaluated in the field with a microrelief meter having pins spaced 50.8 mm apart from ridge to ridge positions. Additional readings at 50.8-mm intervals along 1 m of row resulted in 400 pin readings per setting. Roughness was determined in subplots of only two replications.

Sorghum emergence was evaluated by counting seedlings that emerged in 2-m-long row sections at two sites per subplot. Seedlings were initially counted each day, then less frequently until no further emergence occurred.

[3] This paper reports the results of research only. Mention of a pesticide in this paper does not constitute a recommendation for use by the U.S. Department of Agriculture nor does it imply registration under FIFRA as amended.

[4] Mention of a trade name or product does not constitute a recommendation or endorsement by the U.S. Dep. of Agriculture.

**Table 2—Determinations made on initial wheat crop, soil samples collected during fallow, and sorghum emergence.**

| Determination | Sampling time | Type or method of determination | Sampling depth increment and total depth |
|---|---|---|---|
| Wheat grain yield | Wheat harvest | Field combine | -- |
| Wheat residue yield | Before grain harvest | Clipped from 1-m$^2$ areas | -- |
| Surface residues after tillage | After tillage operations | Visual estimation | -- |
| Precipitation amount | At precipitation events | Standard rain gauge | -- |
| Precipitation intensity | At precipitation events | Recording rain gauge | -- |
| Dry aggregate distribution | Before and after tillage | Rotary sieve | Surface 20–30 mm |
| Organic matter content | Before and after tillage | Jackson (1958) | Surface 20–30 mm |
| Modulus of rupture | Before and after tillage | Briquettes | Surface 20–30 mm |
| Crushing resistance (lab) | Before and after tillage | Briquette fragments with penetrometer | Surface 20–30 mm |
| Crust strength (field) | With time after rainfall or sprinkler irrigation | Soil crust with penetrometer | Surface crust |
| Crust water content (field) | With time after rainfall or sprinkler irrigation | Gravimetric | Surface crust |
| Soil resistance (field) | At or near sorghum planting | Cone penetrometer | To 0.30-m total depth |
| Soil water content (field) | At or near sorghum planting | Gravimetric | 0.05-m increments to 0.30-m depth |
| Random roughness | Before and after tillage | Micro-relief meter | Surface |
| Seedling emergence | With time after sorghum planting | Number emerged per 2-m of row per plot | - |

Data were analyzed by analysis of variance and by Duncan's Multiple Range Test (LeClerg et al., 1962) to establish which differences were significant. Relationships among variables were calculated by methods of Ezekiel and Fox (1959).

## RESULTS AND DISCUSSION

### Wheat Grain and Residue Yields

The initial wheat crops yielded 2.63, 3.95, and 3.16 Mg/ha of grain and 5.4, 6.3, and 5.2 Mg/ha of residue in 1978, 1979, and 1980, respectively. Residues removed for the low residue treatment averaged 2.2, 1.7, and 1.5 Mg/ha in the respective years. Residue removal was relatively low because the wheat was a short-statured cultivar ('TAM wheat 101') and because the wheat was on furrow-irrigated land which precluded cutting the residues close to the base of all plants. Because of the low amount removed, residue-level treatments did not significantly ($P = 0.05$) affect some measured factors. For factors not significantly affected, data reported are averages of both residue-level treatments.

### Precipitation

Monthly precipation during fallow is given in Table 3. Also given are some characteristics for the greatest storm during the month, provided total precipitation for the storm equaled or exceeded 13 mm. Storms after which CS were measured are identified. A record storm totaling 143 mm occurred in September 1978, with a maximum intensity of 65 mm/h for a 44-min period. More intense storms occurred in May of 1979 and 1981, but duration at maximum intensity was only 18 and 20 min in the respective years. Precipitation will be further discussed in connection with CS and RR.

### Surface Residues after Tillage

Tillage method and residue level treatments significantly affected the amounts of residue remaining on the surface after initial tillage and at sorghum planting (Table 4). For the low residue level treatment, MT and RT resulted in 10% or less, DT in about 43%, and ST in about 86% of the surface residues remaining after the initial operation as compared with the NT treatment. For the high residue level treatment, amounts remaining were about 16% for MT and RT, 64% for DT, and 92% for ST as compared with NT. On NT plots, estimated amounts were less than amounts determined by clipping the entire plants. The harvester shredded the residue, which greatly reduced its size. These shredded residues along with the chaff were difficult to estimate accurately and resulted in lower estimates than the amounts determined by clipping.

Surface residues further decreased with time during fallow. At sorghum planting, low residue level treatment subplots for MT, DT, and RT were almost bare, and ST and NT subplots had about 20 and 50%, respectively, of the original residues remaining. On high residue level subplots, only the ST and NT treatments resulted in substantial amounts of surface residues at sorghum planting.

### Dry Aggregate Distribution

Mean weight diameters (MWD) (Kemper and Chepil, 1965), calculated from the dry sieving results, were similar for samples taken before initial tillage (Table 4). Residue level treatments did not significantly affect MWD.

Based on multiple linear regression analyses, MWD was significantly related to precipitation recency of tillage, and type of tillage (Table 5). For the analyses, recency of tillage was represented by 1 or 0 when tillage had or had not been recently performed, respectively. Types of tillage were represented by 0, 1, 2, and 3 for NT, loosening (ST), mixing (DT and RT), and inverting (MT) methods, respectively.

Initial tillage with the moldboard plow resulted in the highest MWD. Next highest MWD's resulted from

**Table 3—Precipitation amounts and characteristics during fallow periods at Bushland, TX, 1978–81.**

| Factor considered | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Apr. | May | Fallow period total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Month of fallow | | | | | | | |
| | | | 1978–79 | | | | | | | | | |
| Total for month, mm | 13 | 40 | 156 | 7 | 24 | -- | 14 | 8 | 25 | 10 | 52 | 349 |
| Total for major storm, mm | 13 | -- | 143† | -- | -- | -- | -- | -- | -- | -- | 45† | |
| Duration of major storm, min | 60 | -- | 1320 | -- | -- | -- | -- | -- | -- | -- | 490 | |
| Maximum intensity of major storm, mm/h | 22 | -- | 65 | -- | -- | -- | -- | -- | -- | -- | 85 | |
| Duration at maximum intensity, min | 35 | -- | 44 | -- | -- | -- | -- | -- | -- | -- | 18 | |
| | | | 1979–80 | | | | | | | | | |
| Total for month, mm | 49 | 68 | 5 | 40 | 12 | -- | 17 | -- | 39 | 19 | 110 | 359 |
| Total for major storm, mm | 21 | 26 | -- | 40† | -- | -- | 17 | -- | -- | 15† | 34† | |
| Duration of major storm, min | 64 | 40 | -- | ‡ | -- | -- | 300 | -- | -- | 140 | 360 | |
| Maximum intensity of major storm, mm/h | 21 | 46 | -- | ‡ | -- | -- | 5§ | -- | -- | 8 | 10 | |
| Duration at maximum intensity, min | 47 | 30 | -- | ‡ | -- | -- | 110 | -- | -- | 80 | 106 | |
| | | | 1980–81 | | | | | | | | | |
| Total for month, mm | 32 | 43 | 27 | -- | 9 | -- | -- | -- | 54 | 6 | 72 | 242 |
| Total for major storm, mm | -- | 17 | 21 | -- | -- | -- | -- | -- | 19† | -- | 39† | |
| Duration of major storm, min | -- | 450 | ‡ | -- | -- | -- | -- | -- | 480 | -- | 73 | |
| Maximum intensity of major storm, mm/h | -- | 4 | ‡ | -- | -- | -- | -- | -- | 2 | -- | 88 | |
| Duration at maximum intensity, min | -- | 180 | ‡ | -- | -- | -- | -- | -- | 210 | -- | 20 | |

† Rainstorms after which crust strengths were determined.
‡ Recording rain gauge did not function properly.
§ Rain and snow.

Table 4—Effect of tillage method and time of measurement on surface residues and some soil factors during fallow after wheat, Bushland, TX, 1978–1981.

| Factor measured and time of measurement | Residue level | Tillage method† MT | DT | RT | ST | NT | Avg. |
|---|---|---|---|---|---|---|---|
| Surface residues, Mg/ha | | | | | | | |
| After initial tillage | Low | 0.1 | 1.5 | 0.4 | 3.0 | 3.5 | 1.7 |
| | High | 1.0 | 3.9 | 0.9 | 5.6 | 6.1 | 3.5 |
| | Avg. | 0.6 | 2.7 | 0.7 | 4.3 | 4.8 | |
| At sorghum planting | Low | <0.1 | 0.2 | <0.1 | 0.6 | 1.8 | 0.6 |
| | High | 0.3 | 0.6 | 0.3 | 2.5 | 4.1 | 1.6 |
| | Avg. | 0.2 | 0.4 | 0.2 | 1.6 | 3.0 | |
| Overall avg. | | 0.4 | 1.6 | 0.4 | 2.9 | 3.9 | |
| Dry aggregates—MWD, mm | | | | | | | |
| Before initial tillage | Avg. | 6.6 | 6.6 | 6.4 | 6.3 | 6.7 | 6.5d* |
| After initial tillage | Avg. | 22.6 | 15.2 | 13.6 | 8.6 | 6.7 | 13.3 a |
| Before 2nd tillage | Avg. | 15.3 | 11.7 | 11.3 | 9.8 | 6.7 | 11.0 bc |
| After 2nd tillage | Avg. | 17.4 | 13.7 | 11.9 | 11.3 | 6.5 | 12.2 ab |
| Before last tillage | Avg. | 7.7 | 6.4 | 6.6 | 7.2 | 6.5 | 6.9 d |
| After last tillage | Avg. | 10.6 | 10.8 | 11.2 | 11.5 | 7.7 | 10.4 c |
| Avg. | | 13.4a* | 10.7b | 10.2b | 9.1c | 6.8d | |
| Protected LSD (tillage × time – 0.05 level) = 3.0 mm | | | | | | | |
| Organic matter, g/kg | | | | | | | |
| Before initial tillage | Avg. | 19.7 | 19.8 | 19.9 | 19.8 | 20.1 | 19.9a* |
| After initial tillage | Avg. | 18.2 | 19.7 | 20.1 | 19.6 | 19.9 | 19.5 a |
| Before 2nd tillage | Avg. | 17.8 | 19.2 | 20.2 | 19.8 | 20.2 | 19.4 a |
| After 2nd tillage | Avg. | 18.4 | 19.7 | 19.8 | 19.7 | 20.4 | 19.6 a |
| Before last tillage | Avg. | 17.8 | 19.3 | 19.3 | 18.8 | 19.1 | 18.8 b |
| After last tillage | Avg. | 17.8 | 19.2 | 19.1 | 19.4 | 19.0 | 18.9 b |
| Avg. | | 18.3b* | 19.5 a | 19.7a | 19.5a | 19.8a | |
| Modulus of rupture, kPa | | | | | | | |
| Before initial tillage | Avg. | 17.4 | 15.9 | 13.8 | 14.5 | 17.1 | 15.7c* |
| After initial tillage | Avg. | 64.2 | 33.1 | 40.2 | 19.7 | 16.4 | 34.7 a |
| Before 2nd tillage | Avg. | 41.3 | 24.8 | 33.3 | 22.0 | 26.5 | 29.5 b |
| After 2nd tillage | Avg. | 56.6 | 32.9 | 39.3 | 28.7 | 21.4 | 35.8 a |
| Before last tillage | Avg. | 21.2 | 14.4 | 16.4 | 16.1 | 14.2 | 16.5 c |
| After last tillage | Avg. | 24.0 | 18.2 | 20.2 | 22.0 | 11.7 | 19.2 c |
| Avg. | | 37.5a* | 23.2c | 27.2b | 20.5d | 17.9e | |
| Protected LSD (tillage × time – 0.05 level) = 5.7 kPa | | | | | | | |
| Crushing resistance, MPa | | | | | | | |
| Before initial tillage | Avg. | 0.39 | 0.37 | 0.30 | 0.32 | 0.35 | 0.35c* |
| After initial tillage | Avg. | 1.46 | 0.74 | 0.87 | 0.44 | 0.36 | 0.77 a |
| Before 2nd tillage | Avg. | 0.93 | 0.55 | 0.73 | 0.45 | 0.46 | 0.62 b |
| After 2nd tillage | Avg. | 1.80 | 0.73 | 0.85 | 0.64 | 0.47 | 0.80 a |
| Before last tillage | Avg. | 0.46 | 0.32 | 0.36 | 0.35 | 0.31 | 0.36 c |
| After last tillage | Avg. | 0.56 | 0.40 | 0.41 | 0.50 | 0.23 | 0.42 c |
| Avg. | | 0.85a* | 0.52c | 0.59b | 0.45d | 0.36e | |
| Protected LSD (tillage × time – 0.05) level = 0.14 MPa | | | | | | | |
| Random roughness, mm | | | | | | | |
| Before initial tillage | Avg. | 7.9 | 9.0 | 7.9 | 7.7 | 8.2 | 8.1cd* |
| After initial tillage | Avg. | 30.3 | 20.8 | 11.2 | 15.7 | 8.2 | 17.2a |
| Before 2nd tillage | Avg. | 23.3 | 15.3 | 9.6 | 12.9 | 8.2 | 13.9b |
| After 2nd tillage | Avg. | 15.9 | 13.9 | 12.0 | 16.1 | 7.9 | 13.2b |
| Before last tillage | Avg. | 9.5 | 8.9 | 7.4 | 10.5 | 7.8 | 8.8c |
| After last tillage | Avg. | 7.6 | 7.5 | 7.9 | 8.7 | 7.5 | 7.8d |
| Avg. | | 15.8a* | 12.6b | 9.3c | 12.0b | 8.0d | |
| Protected LSD (tillage × time – 0.05 level) = 1.7 mm | | | | | | | |

* Row or column values followed by the same letter or letters are not significantly different at the 0.05 level (Duncan's Multiple Range Test).

† Tillage methods are: MT—moldboard, DT—disk, RT—rotary, ST—sweep, and NT—no-tillage.

DT, RT, and ST in decreasing order. As expected, no change in MWD occurred for the NT treatment. Furthermore, the MWD for NT did not change significantly during fallow (Table 4).

For the MT and DT treatments, MWD's decreased significantly before the second tillage due to clod disintegration resulting from rainfall and soil wetting and drying. The second tillage operation did not significantly affect MWD for any treatment, but further decreases occurred for all except the NT treatment before the last tillage operation. These decreases resulted from overwinter freezing and thawing and wetting and drying. The increase in MWD's after the last tillage resulted from larger aggregates being brought to the surface by the tillage operations, which formed ridges and furrows.

Although NT resulted in the lowest MWD, which suggests a greater wind erosion susceptibility on these than on other plots, wind erosion was not a problem because the surfaces were protected by residues. However, even with other treatments for which the MWD's were similarly low before the last tillage operation, wind erosion was not a problem.

## Organic Matter Content

Soil organic matter (OM) content was significantly affected by tillage method and time of sampling, but not by residue level treatments (Table 4). Soil OM content was significantly different among fallow periods (0.05 level) and the tillage × fallow period and time of sampling × fallow period interactions were significant at the 0.01 level (data not shown).

As compared to other treatments, MT resulted in a lower average OM content. This tillage method inverted the plow layer and thereby placed the soil containing the most OM at the bottom of the tillage layer. After initial tillage, soil containing less OM was sampled. Relationships among OM content and other factors are further discussed in a later section.

Organic matter contents averaged across tillage methods and times of sampling were 19.0, 19.3, and 19.8 g/kg (dry weight basis) in the 1978–79, 1979–80 and 1980–81 fallow periods, respectively (LSD = 0.56g/kg at $P = 0.05$). Slight differences in managing the areas before establishing the plots possibly resulted in the different OM contents at the initial sampling, which were 20.1, 19.1, and 20.5 g/kg in the respective years. These initial differences, along with differences in amount and distribution of precipitation during the fallow periods (Table 3), possibly resulted in the average differences in OM contents among fallow periods.

The significant tillage method × fallow period interaction effect on OM resulted mainly from MT. As compared with other methods, MT resulted in greater decreases in OM contents during fallow when the OM content was relatively high initially (1978–79 and 1980–81). When initially low (1979–80), the decrease resulting from MT was much lower. The significant time of sampling × fallow period interaction effect resulted from differences in initial OM contents and precipitation amount and distribution. Organic matter contents decreased significantly during the 1978–79 and 1980–81 fallow periods when initial contents were relatively high, but not during the 1979-80 fallow when the initial content was lower. Organic matter decreased about twice as much during the 1978–79 period, when precipitation was relatively high, than during the 1980–81 period, when precipitation was about 30% lower.

Table 5—Summary of multiple linear regression analyses associating various soil factors with soil OM content, precipitation, and recency and type of tillage.†‡

| Dependent variable | Intercept | Independent variables§ Organic matter | Precip. | Recency of tillage | Tillage type | SE¶ | *R*# |
|---|---|---|---|---|---|---|---|
| | | equation coefficients†† | | | | | |
| Mean weight diameter—dry aggregates, mm | 9.813 | -- | −0.0091(3)* | −3.5171(2)** | 3.7832(1)** | 3.204 | 0.686** |
| Modulus of rupture, kPa | 102.946 | −4.2736(2)** | -- | -- | 7.0720(1)** | 1.320 | 0.550** |
| Crushing resistance, MPa | 2.164 | −0.0894(2)** | -- | -- | 0.1681(1)** | 0.297 | 0.559** |
| Random roughness, mm | 15.740 | -- | −0.0310(1)* | -- | -- | 13.950 | −0.227* |

† Rankings are based on standardized regression coefficients and are shown in parentheses immediately after the equation coefficients. Rankings are in order from 1 (highest) to 3 (lowest).
‡ Levels of significance of equation coefficients are based on the *t*-test of the partial regression coefficients. Levels of significance are shown after rankings and are * (0.05) and ** (0.01).
§ Independent variables are OM (organic matter, g/kg), precip. (precipitation since last tillage operation, mm), recency of tillage, (0 for none and 1 for tillage), and tillage type (0 for none, 1 for soil loosening, 2 for soil mixing, and 3 for soil inverting).
¶ Standard error of estimate.
# Coefficient of correlation. Levels of significance are * (0.05) and ** (0.01).
†† Results are shown only for the analyses for which the partial regression coefficients were significant.

## Modulus of Rupture

Moduli of rupture (MR) of briquettes were significantly affected by tillage method, time of sampling, and fallow period. Interactions among these factors were also significant. Data for tillage method and time of sampling are shown in Table 4. The average MR was highest for MT and lowest for NT.

The first two, but not the last, tillage operations resulted in significant increases in MR. For initial tillage, the largest increase resulted from MT. Increases for RT and DT were successively less. Sweep tillage had no significant effect at the first operation and NT, as expected, had no effect.

The MR decreased significantly for MT, DT, and RT; did not change significantly for ST; and increased significantly for NT for samples collected before the second tillage as compared to those collected after the first tillage. Order of increase in MR resulting from the second tillage was MT (largest), DT, ST, and RT (smallest). The MR decreased in all cases between the second and last tillage operation. The decrease was greatest for MT and least for NT.

The MT, DT, and RT treatments contributed most to the significant tillage method × time of sampling interaction effect on MR. Sweep tillage usually had a small effect and NT had no effect for samples obtained before or after a given tillage. The MR, however, increased significantly between the time of first and second tillage for samples from NT plots, but decreased or did not change significantly with other tillage methods. The reason for the increase is not known.

Multiple linear regression analyses indicated that MR was significantly related to soil OM content and type of tillage. The effect of recency of tillage, amount of precipitation, and surface residues was not significant (Table 5).

The major effect of type of tillage on MR apparently is related to the effects of tillage on OM distribution in soil. Moldboard tillage, which resulted in the highest MR, also resulted in the lowest average OM content (Table 4). Tillage that brought soil low in OM to the surface resulted in an increased MR. This negative relationship between OM matter content and MR was confirmed by the regression analyses (Table 5).

The significant decreases in MR with time after tillage suggest that major tillage, when used, should be performed as soon as possible after crop harvest. Such practice should minimize the adverse effect of inverting or mixing tillage on soil crust strength and subsequent seedling emergence problems. These problems, however, can largely be avoided by use of conservation tillage systems (for example, NT), which resulted in the lowest MR after the last tillage.

## Crushing Resistance (Laboratory)

The crushing resistance (CR) results obtained with a penetrometer on fragments of briquettes from the MR determinations closely paralleled the MR results (Table 4). Although the values were different, tillage methods and times of measurement resulted in identical statistical differences among average values, as determined by the Duncan Multiple Range Test.

For the relationship between MR and CR, $r = 0.977$. This was not unexpected because the determinations involved the same briquettes. Also, Unger (1982a) reported a similarly high relationship between the two determinations ($r = 0.997$). The same factors that affected MR, as discussed previously, also affected CR (Table 5).

Both methods of evaluating briquettes are useful for evaluating the effects of tillage on the potential for soil crusting. Because CR of briquettes and soil crusts under field conditions are both measured with a penetrometer, determining CR in the laboratory should be useful for evaluating the potential for seedling emergence problems under field conditions. The CR measurements are accomplished with much simpler equipment than the MR measurements.

## Crust Strength and Water Content (Field)

Crust Strength (CS) and associated crust water content (WC) data obtained after a major rainstorm in 1978 are given in Table 6. Data obtained near or after sorghum planting are given in Table 7.

Crust strengths after the major rainstorm in September 1978 (Table 3) were significantly different due to tillage methods, residue levels, and day of sampling (day after rainfall). The tillage method × sampling day interaction effect on CS was also statistically significant. On the first sampling day, CS resulting from

**Table 6—Effect of tillage method, residue level, and time after rainfall on soil crust strength and water content after a major rainstorm at Bushland, TX, Sept. 1978.**

| | | Crust strength | | | | | | | Crust water content | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Tillage method† | | | | | Averages | | Tillage method† | | | | | Averages | |
| Time after rainfall | Residue level | MT | DT | RT | ST | NT | Residue level | Day | MT | DT | RT | ST | NT | Residue level | Day |
| days | | MPa | | | | | | | kg/kg | | | | | | |
| 8 | Low | 0.67 | 0.53 | 0.64 | 0.36 | 0.44 | 0.53 | | 0.197 | 0.232 | 0.158 | 0.226 | 0.189 | 0.200 | |
| | High | 0.64 | 0.44 | 0.58 | 0.31 | 0.31 | 0.46 | 0.50c* | 0.231 | 0.251 | 0.173 | 0.300 | 0.290 | 0.249 | 0.225a* |
| | Avg. | 0.66 | 0.49 | 0.61 | 0.34 | 0.38 | | | 0.214 | 0.242 | 0.166 | 0.263 | 0.240 | | |
| 9 | Low | 0.84 | 0.72 | 0.64 | 0.47 | 0.50 | 0.63 | | 0.161 | 0.142 | 0.073 | 0.127 | 0.123 | 0.125 | |
| | High | 0.87 | 0.55 | 0.56 | 0.31 | 0.39 | 0.54 | 0.59bc | 0.164 | 0.174 | 0.084 | 0.239 | 0.213 | 0.175 | 0.150b |
| | Avg. | 0.86 | 0.64 | 0.60 | 0.39 | 0.45 | | | 0.163 | 0.158 | 0.079 | 0.183 | 0.168 | | |
| 10 | Low | 1.22 | 0.73 | 0.67 | 0.44 | 0.45 | 0.70 | | 0.133 | 0.102 | 0.072 | 0.090 | 0.088 | 0.097 | |
| | High | 1.14 | 0.72 | 0.59 | 0.37 | 0.33 | 0.63 | 0.67b | 0.123 | 0.120 | 0.062 | 0.217 | 0.175 | 0.139 | 0.118c |
| | Avg. | 1.18 | 0.73 | 0.63 | 0.41 | 0.39 | | | 0.128 | 0.111 | 0.067 | 0.154 | 0.132 | | |
| 12 | Low | 1.47 | 0.87 | 0.83 | 0.61 | 0.56 | 0.87 | | 0.088 | 0.080 | 0.047 | 0.071 | 0.054 | 0.068 | |
| | High | 1.36 | 0.81 | 0.80 | 0.52 | 0.42 | 0.78 | 0.83a | 0.103 | 0.099 | 0.050 | 0.125 | 0.114 | 0.098 | 0.083d |
| | Avg. | 1.42 | 0.84 | 0.82 | 0.57 | 0.49 | | | 0.096 | 0.090 | 0.049 | 0.098 | 0.084 | | |
| 16 | Low | 1.76 | 1.00 | 0.77 | 0.58 | 0.48 | 0.92 | | 0.045 | 0.029 | 0.025 | 0.034 | 0.024 | 0.031 | |
| | High | 1.50 | 0.92 | 0.72 | 0.50 | 0.42 | 0.87 | 0.90a | 0.045 | 0.031 | 0.029 | 0.044 | 0.036 | 0.037 | 0.034e |
| | Avg. | 1.63 | 0.96 | 0.75 | 0.54 | 0.45 | | | 0.045 | 0.030 | 0.027 | 0.039 | 0.030 | | |
| | | Protected LSD (tillage × date – 0.05 level) = 0.12 MPa | | | | | | | Protected LSD (tillage × date – 0.05 level) = 0.022 kg/kg | | | | | | |
| Residue level avg. | Low | 1.19 | 0.77 | 0.71 | 0.49 | 0.49 | 0.73a* | | 0.125 | 0.117 | 0.075 | 0.110 | 0.096 | 0.105b* | |
| | High | 1.10 | 0.69 | 0.65 | 0.40 | 0.37 | 0.64b | | 0.133 | 0.135 | 0.080 | 0.185 | 0.166 | 0.140a | |
| | | Protected LSD (tillage × residue level – 0.05 level) = N.S. | | | | | | | Protected LSD (tillage × residue level – 0.05 level) = 0.014 kg/kg | | | | | | |
| Overall avg. | | 1.15a* | 0.73b | 0.68b | 0.45c | 0.43c | | | 0.129b* | 0.126b | 0.078c | 14.7a | 13.1b | | |
| | | Protected LSD (residue level × date – 0.05 level) = NS | | | | | | | Protected LSD (residue level × date – 0.05 level) = 0.09 kg/kg | | | | | | |

* Row or column values for a given factor followed by the same letter or letters are not significantly different at the 0.05 level (Duncan's multiple range test).
† Tillage methods are: MT—moldboard, DT—disk, RT—rotary, ST—sweep, and NT—no-tillage.

MT and RT were similar and both were significantly higher than for other tillage methods. Sweep and NT resulted in similar low CS. On subsequent days, MT resulted in significant increases in CS, with the final CS being 147% greater than at the first sampling. Strength increases from the first to last sampling were 96, 59, 23, and 18% for the DT, ST, RT, and NT treatments, respectively. However, values for NT were not significantly different for any sampling day. The average CS was highest for MT and similarly low for ST and NT.

Average CS were higher on low residue subplots than on high residue subplots, and increased from the first to last sampling day. The CS were related in part to crust WC, with CS generally increasing with decreases in crust WC. However, there were exceptions. Moldboard tillage resulted in the highest CS at the final sampling, yet the crust WC at that sampling was also significantly higher for MT than for some other tillage treatments. Also, CS did not change significantly throughout the sampling period for the NT treatment, yet an eightfold decrease in crust WC occurred with this treatment. Rotary tillage resulted in an intermediate average CS, but the lowest average crust WC. Simple linear regression analysis revealed that crust WC ($x$) accounted for only 19% of the variation in CS ($y$), for which the equation is $y = -0.0189x + 0.9203$, with $r = -0.439$ ($P = 0.01$). Other contributing factors undoubtedly were soil OM content and the protection afforded by surface residues against raindrop impact on the soil surface during the rainstorm. Moldboard tillage resulted in the lowest OM content of the surface soil after the initial tillage operation (Table 4) and the highest random roughness (RR) of the surface (Table 4, discussed in more detail later), which was almost devoid of residues (Table 4). Consequently, the rainstorm caused major disintegration of surface clods, decrease in RR, rearrangement of soil particles, and a resultant high CS. Other tillage plots with more surface residues and/or smoother surfaces experienced smaller decreases in RR and less rearrangement of soil particles, and consequently lower CS.

The CS measured near or after sorghum planting were low compared with those measured after the major rainstorm in 1978 because neither the irrigations nor the rainstorm in 1981 applied water at an intensity as high as that of the major rainstorm. The CS were low, even though the crust WC at the time of determination were also relatively low (Table 7). Crust sampling was delayed until near the time of expected seedling emergence; hence, the relatively dry soil crusts as compared to those measured after previous rainstorms. In 1979, average CS increased significantly on successive sampling days as the WC decreased significantly, but neither tillage nor residue level treatments had a significant effect. In 1980, NT resulted in the lowest and RT resulted in the highest CS. The differences among tillage treatments were significant, but relatively small. The generally small differences in CS among tillage treatments are attributed to all plots, except NT, having been tilled several times by the time the measurements were made, with the last operation being used for seedbed preparation. These tillage operations mixed the plow layer, thus resulting in rather uniform surface soil at the end of fallow and the generally similar CS.

**Table 7—Effect of tillage method, residue level, and day of determination on soil crust strength and water content after sprinkler irrigation or major rainfall near or after planting sorghum at Bushland, TX, 1979–81.**

| Year and day after irrigation or major rainfall | Residue level | Crust strength: Tillage method† MT | DT | RT | ST | NT | Averages: Residue level | Day | Crust water content: Tillage method† MT | DT | RT | ST | NT | Averages: Residue level | Day |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MPa | | | | | | | kg/kg | | | | | | |
| 1979 | | | | | | | | | | | | | | | |
| 2 | Low | 0.43 | 0.48 | 0.46 | 0.42 | 0.58 | 0.47 | | 0.070 | 0.088 | 0.062 | 0.077 | 0.091 | 0.078 | |
| | High | 0.45 | 0.45 | 0.41 | 0.52 | 0.46 | 0.46 | 0.47c* | 0.097 | 0.085 | 0.059 | 0.099 | 0.084 | 0.085 | 0.082a* |
| | Avg. | 0.44 | 0.47 | 0.44 | 0.47 | 0.52 | | | 0.084 | 0.087 | 0.061 | 0.088 | 0.088 | | |
| 3 | Low | 0.46 | 0.57 | 0.50 | 0.50 | 0.56 | 0.52 | | 0.064 | 0.067 | 0.065 | 0.056 | 0.079 | 0.066 | |
| | High | 0.47 | 0.55 | 0.48 | 0.62 | 0.53 | 0.53 | 0.53b | 0.070 | 0.070 | 0.055 | 0.083 | 0.073 | 0.070 | 0.068b |
| | Avg. | 0.47 | 0.56 | 0.49 | 0.56 | 0.55 | | | 0.067 | 0.069 | 0.060 | 0.070 | 0.076 | | |
| 4 | Low | 0.54 | 0.60 | 0.55 | 0.48 | 0.55 | 0.54 | | 0.030 | 0.036 | 0.030 | 0.027 | 0.048 | 0.034 | |
| | High | 0.59 | 0.61 | 0.49 | 0.75 | 0.54 | 0.60 | 0.57a | 0.053 | 0.038 | 0.029 | 0.040 | 0.062 | 0.044 | 0.039c |
| | Avg. | 0.57 | 0.61 | 0.52 | 0.62 | 0.55 | | | 0.042 | 0.037 | 0.030 | 0.034 | 0.055 | | |
| Residue level avg. | Low | 0.48 | 0.55 | 0.50 | 0.47 | 0.56 | 0.51a* | | 0.055 | 0.064 | 0.052 | 0.053 | 0.073 | 0.059a* | |
| | High | 0.50 | 0.54 | 0.46 | 0.63 | 0.51 | 0.53a | | 0.073 | 0.064 | 0.048 | 0.074 | 0.073 | 0.066a | |
| Overall avg. | | 0.49a* | 0.55a | 0.48a | 0.55a | 0.54a | | | 0.064a* | 0.064a | 0.050b | 0.064a | 0.073a | | |
| 1980 | | | | | | | | | | | | | | | |
| 2 | Low | 0.34 | 0.43 | 0.42 | 0.36 | 0.31 | 0.37 | | 0.041 | 0.049 | 0.053 | 0.031 | 0.037 | 0.042 | |
| | High | 0.37 | 0.36 | 0.47 | 0.43 | 0.28 | 0.38 | 0.38a* | 0.033 | 0.045 | 0.045 | 0.037 | 0.051 | 0.042 | 0.042a* |
| | Avg. | 0.36 | 0.40 | 0.45 | 0.40 | 0.30 | | | 0.037 | 0.047 | 0.049 | 0.034 | 0.044 | | |
| 3 | Low | 0.30 | 0.39 | 0.38 | 0.37 | 0.27 | 2.34 | | 0.024 | 0.024 | 0.025 | 0.028 | 0.024 | 0.025 | |
| | High | 0.35 | 0.35 | 0.40 | 0.41 | 0.22 | 0.35 | 0.35a | 0.021 | 0.026 | 0.026 | 0.026 | 0.033 | 0.026 | 0.026a |
| | Avg. | 0.33 | 0.37 | 0.39 | 0.39 | 0.25 | | | 0.023 | 0.025 | 0.026 | 0.027 | 0.029 | | |
| Residue level | | 0.32 | 0.41 | 0.40 | 0.37 | 0.29 | 0.36a* | | 0.033 | 0.037 | 0.039 | 0.030 | 0.031 | 0.034a* | |
| avg. | | 0.36 | 0.36 | 0.44 | 0.42 | 0.25 | 0.37a | | 0.027 | 0.036 | 0.036 | 0.032 | 0.042 | 0.035a | |
| Overall avg. | | 0.34b* | 0.39ab | 0.42a | 0.40ab | 0.27c | | | 0.030a* | 0.037a | 0.038a | 0.031a | 0.037a | | |
| 1981 | | | | | | | | | | | | | | | |
| 6 | Low | 0.54 | 0.57 | 0.58 | 0.50 | 0.43 | 0.52 | | 0.090 | 0.122 | 0.113 | 0.108 | 0.096 | 0.106 | |
| | High | 0.55 | 0.50 | 0.51 | 0.49 | 0.35 | 0.38 | 0.50a* | 0.089 | 0.125 | 0.099 | 0.142 | 0.156 | 0.122 | 0.114a* |
| | Avg. | 0.55 | 0.54 | 0.55 | 0.50 | 0.39 | | | 0.090 | 0.124 | 0.106 | 0.125 | 0.126 | | |
| 7 | Low | 0.56 | 0.50 | 0.58 | 0.45 | 0.29 | 0.38 | | 0.049 | 0.061 | 0.055 | 0.060 | 0.052 | 0.055 | |
| | High | 0.44 | 0.51 | 0.47 | 0.43 | 0.30 | 0.43 | 0.46b | 0.045 | 0.062 | 0.052 | 0.082 | 0.070 | 0.062 | 0.059c |
| | Avg. | 0.50 | 0.51 | 0.53 | 0.44 | 0.30 | | | 0.047 | 0.062 | 0.054 | 0.071 | 0.061 | 0 | |
| 12 | Low | 0.55 | 0.53 | 0.53 | 0.45 | 0.33 | 0.48 | | 0.080 | 0.097 | 0.091 | 0.105 | 0.083 | 0.091 | |
| | High | 0.53 | 0.57 | 0.47 | 0.38 | 0.33 | 0.46 | 0.47b | 0.076 | 0.109 | 0.086 | 0.139 | 0.119 | 0.106 | 0.099b |
| | Avg. | 0.54 | 0.55 | 0.50 | 0.42 | 0.33 | | | 0.078 | 0.103 | 0.089 | 0.122 | 0.101 | | |
| 13 | Low | 0.58 | 0.57 | 0.52 | 0.47 | 0.32 | 0.49 | | 0.050 | 0.057 | 0.036 | 0.059 | 0.044 | 0.049 | |
| | High | 0.47 | 0.55 | 0.43 | 0.42 | 0.30 | 0.43 | 0.46b | 0.036 | 0.049 | 0.048 | 0.077 | 0.068 | 0.056 | 0.053c |
| | Avg. | 0.53 | 0.56 | 0.48 | 0.45 | 0.31 | | | 0.043 | 0.053 | 0.042 | 0.068 | 0.056 | | |
| Residue level avg. | Low | 0.56 | 0.54 | 0.55 | 0.47 | 0.34 | 0.49a* | | 0.067 | 0.084 | 0.074 | 0.083 | 0.069 | 0.075b* | |
| | High | 0.50 | 0.53 | 0.47 | 0.43 | 0.32 | 0.45b | | 0.062 | 0.086 | 0.071 | 0.110 | 0.103 | 0.086a | |
| | | | | | | | | | Protected LSD (tillage × residue level – 0.05 level) = 0.014 kg/kg | | | | | | |
| Overall avg. | | 0.53a* | 0.54a | 0.51a | 0.45b | 0.33c | | | 0.065c* | 0.085b | 0.073c | 0.097c | 0.086b | | |

* Row or column values for a given factor followed by the same letter or letters are not significantly different at the 0.05 level (Duncan's multiple range test).
† Tillage methods are: MT—moldboard, DT—disk, RT—rotary, ST—sweep, and NT—no-tillage.

All variables (tillage method, residue level, and sampling days) significantly affected CS after the rainstorm in 1981. Additional rain between the second and third sampling dates (41 mm on 29–31 May) significantly increased crust WC on the third sampling day, but had no effect on CS.

In contrast to the highly significant ($P = 0.01$) negative relationship between CS and crust WC after the major rainstorm in 1978, relationships near or after planting between CS ($y$) and crust WC ($x$) were erratic and sometimes not statistically significant. The results, based on linear regressions, were: $y = -0.0134x + 0.6107$ ($r = -0.345$, $P = 0.10$) in 1979, $y = 0.0128x + 0.3169$ ($r = 0.213$, $P = 0.40$) in 1980, $y = -0.0010x + 0.4795$ ($r = -0.036$, NS.) in 1981, and $y = 0.0078x + 0.4196$ ($r = 0.238$, $P = 0.05$) for combined data. The low correlation is attributed to low WC when the measurements were made, which in turn are attributed to the low amounts of surface residues at the time of measurement, even in the NT plots. On NT plots, relatively large amounts of residue covered part of the surface, but the ridge tops where the sorghum was planted and where the measurements were made were essentially devoid of residues.

### Soil Penetration Resistance and Water Content

Data for soil PR and associated WC obtained after sorghum planting in 1979 and 1981 are given in Table 8. Tillage methods significantly affected average PR each year. In 1979, average PR was highest for DT and NT (identical), intermediate for RT, and lowest for MT and ST. In 1981, average PR was higher for DT than for other methods. Residue level treatments had no statistically significant effects, but PR in-

Table 8—Soil penetration resistances (PR) and associated soil water contents (WC) determined at sorghum planting time at Bushland, TX, 1979 and 1981.

| Year and depth (m) | Tillage method† MT | | DT | | RT | | ST | | NT | | Avg. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PR | WC | PR | WC | PR | WC | PR | WC | PR | WC | PR | WC |
| | MPa | kg/kg | MPa | kg/kg | MPa | kg/kg | MPa | kg/kg | MPa | kg/kg | MPa | kg/kg |
| 1979 | | | | | | | | | | | | |
| 0.05 | 0.03 | 0.196 | 0.03 | 0.192 | 0.01 | 0.187 | 0.02 | 0.219 | 0.05 | 0.203 | 0.03f* | 0.199z* |
| 0.10 | 0.35 | 0.212 | 0.49 | 0.198 | 0.14 | 0.200 | 0.23 | 0.221 | 0.45 | 0.209 | 0.34e | 0.208y |
| 0.15 | 0.67 | 0.228 | 1.04 | 0.203 | 0.54 | 0.212 | 0.58 | 0.223 | 0.89 | 0.215 | 0.75d | 0.216x |
| 0.20 | 1.07 | 0.222 | 1.52 | 0.211 | 0.37 | 0.207 | 1.12 | 0.220 | 1.46 | 0.218 | 1.31c | 0.216x |
| 0.25 | 1.56 | 0.224 | 1.91 | 0.212 | 1.91 | 0.206 | 1.53 | 0.221 | 1.97 | 0.216 | 1.77b | 0.216x |
| 0.30 | 1.95 | 0.225 | 2.12 | 0.213 | 2.29 | 0.205 | 1.87 | 0.222 | 2.31 | 0.213 | 2.11a | 0.216x |
| Avg. | 0.94b* | 0.218xy | 1.19a | 0.205z | 1.04ab | 0.203z | 0.89b | 0.221x | 1.19a | 0.212y | | |
| Protected LSD (depth × tillage – 0.05 level) = 0.16 MPa for PR and 0.010 kg/kg for WC | | | | | | | | | | | | |
| 1981 | | | | | | | | | | | | |
| 0.05 | 0.06 | 0.150 | 0.07 | 0.131 | 0.05 | 0.150 | 0.07 | 0.139 | 0.05 | 0.154 | 0.06f* | 0.145z* |
| 0.10 | 0.20 | 0.190 | 0.33 | 0.172 | 0.16 | 0.195 | 0.25 | 0.178 | 0.33 | 0.194 | 0.26e | 0.186y |
| 0.15 | 0.43 | 0.230 | 1.16 | 0.213 | 0.57 | 0.240 | 0.66 | 0.217 | 0.60 | 0.233 | 0.68d | 0.227x |
| 0.20 | 0.76 | 0.244 | 1.38 | 0.227 | 0.80 | 0.243 | 0.92 | 0.226 | 0.96 | 0.254 | 0.96c | 0.239w |
| 0.25 | 1.30 | 0.248 | 1.41 | 0.232 | 1.17 | 0.246 | 1.12 | 0.231 | 1.25 | 0.253 | 1.25b | 0.242w |
| 0.30 | 1.73 | 0.251 | 1.48 | 0.237 | 1.48 | 0.248 | 1.37 | 0.236 | 1.39 | 0.252 | 1.49a | 0.245w |
| Avg. | 0.77b* | 0.218x | 0.97a | 0.202x | 0.71b | 0.220x | 0.73b | 0.204x | 0.76b | 0.223x | | |
| Protected LSD (depth × tillage – 0.05 level) = 0.17 MPa for PR. (Not significant for WC) | | | | | | | | | | | | |

* Row and column values for PR and WC separately within years that are followed by the same letter or letters are not significantly different at the 0.05 level (Duncan's multiple range test).
† Tillage methods are: MT—moldboard, DT—disk, RT—rotary, ST—sweep, and NT—no-tillage.

creased with soil depth and the depth × tillage interaction was also significant.

In 1979, the significant depth × tillage interaction resulted mainly from high PR at the 0.15- and 0.20-m depths for DT and NT as compared with the other tillage treatments. In 1981, the largest differences compared with other treatments were at the 0.15-, 0.20-, and 0.25-m depths for DT and at the 0.30-m depth for MT. The differences in PR are attributed in part to differences in WC (Table 8). However, the trends were not parallel and treatments with almost identical WC resulted in significantly different PR in some cases (compare DT and ST in 1981). The higher PR, which suggest a more dense soil, did not directly influence water storage in the profile during fallow or grain yields of the subsequent sorghum crop. Average water storage and yield were highest with NT. Water storage with DT was higher than with MT and RT, and yields with DT were higher than with RT (Unger, 1982b).

### Random Roughness

Tillage methods and time of sampling significantly affected RR of the soil surface (Table 4). The tillage × time of sampling interaction was also statistically significant, but residue level treatments had no significant effect. Moldboard tillage resulted in the highest average RR followed in decreasing order by DT, ST, RT, and NT. This same order of RR prevailed after initial tillage. Roughness did not change significantly for the NT treatment throughout the fallow period. After initial tillage, RR progressively decreased for MT and DT treatments. These decreases reflect both soil dispersion due to precipitation and soil pulverization due to DT.

The RR increase due to initial RT was relatively small and the decrease after the initial operation was not significant. The second operation (ST) on RT plots resulted in a significant increase in RR. Thereafter, RR significantly decreased before the last tillage. The trends for ST were similar to those for RT, except that ST resulted in a larger initial increase in RR and a significant decrease due to the last tillage operation. The final RR were similar for all tillage treatments and were not significantly different from the initial RR.

After the initial increase, average RR decreased significantly at subsequent times of sampling, except after the second tillage operation for which the decrease was not significant. The significant tillage × time of sampling interaction resulted from the increases for all, except NT, after the first operation and the subsequent variable decreases with time as already discussed.

The tillage method × fallow period interaction (data not shown) was also significant and resulted from greater RR with DT during the 1978–79 fallow period than during other fallow periods and from lower RR with ST during the 1980–81 fallow period than during the other periods. These differences probably resulted from soil water content differences at the time of tillage. For MT, RT, and NT, average RR did not differ significantly in the different fallow periods.

Surface RR is an important factor in controlling erosion, both by water (Burwell and Larson, 1969; Johnson et al., 1979; Meyer et al., 1970) and by wind (Chepil, 1957; Lyles et al., 1971; Woodruff and Siddoway, 1973) when crop residues are absent. Although neither type of erosion was a problem, the RR afforded by MT early in the fallow period would have provided protection against erosion. Even at the sampling before the second tillage, average RR was greater for MT than for other tillage methods when sampled after the first tillage operation (Table 4).

The high RR with MT, however, also contributed to a high CS because of a greater RR decrease during rainstorms on the unprotected surface. Associated with

**Table 9—Sorghum emergence counts as affected by tillage method, day after planting, and year, Bushland, TX, 1979-81.**

| Year and day | Tillage method† MT | DT | RT | ST | NT | |
|---|---|---|---|---|---|---|
| | Seedlings emerged—1000's/ha | | | | | Avg. |
| 1979— 5 | 59 | 53 | 53 | 35 | 58 | 52d* |
| 6 | 97 | 97 | 91 | 75 | 94 | 91c |
| 7 | 114 | 112 | 107 | 94 | 117 | 109b |
| 9 | 125 | 130 | 113 | 115 | 137 | 124a |
| 13 | 130 | 133 | 118 | 118 | 138 | 127a |
| Avg. | 105ab* | 105ab | 96b | 87c | 109a | |
| 1980— 7 | 8 | 11 | 24 | 14 | 35 | 18c* |
| 8 | 65 | 100 | 120 | 115 | 101 | 100b |
| 9 | 102 | 118 | 132 | 136 | 119 | 121a |
| 11 | 102 | 140 | 137 | 160 | 119 | 131a |
| Avg. | 69c* | 92b | 103a | 106a | 94b | |
| 1981— 5 | 78 | 90 | 57 | 60 | 65 | 70c* |
| 6 | 114 | 110 | 99 | 98 | 99 | 104b |
| 7 | 116 | 117 | 109 | 105 | 106 | 111ab |
| 10 | 120 | 120 | 110 | 108 | 109 | 113a |
| Avg. | 107a* | 109a | 94b | 93b | 95b | |
| Final day avg. | 117a* | 131a | 122a | 129a | 122a | |

* Row or column values for different years and the final day average followed by the same letter or letters are not significantly different at the 0.05 level (Duncan's multiple range test).

† Tillage methods are: MT—moldboard, DT—disk, RT—rotary, ST—sweep, and NT—no-tillage.

the RR decrease was a reorientation of soil particles, which subsequently resulted in the high CS. For example, RR decreased 73% and CS increased 76% after soil drying with MT as compared with DT after the major rainstorm in 1978. The RR decreases and CS increases with MT were even greater when compared with other tillage methods. For conditions after the major rainstorm involving all tillage methods, CS ($y$) was related to RR decrease ($x$) by the equation, $y = 0.631x + 0.345$, with $r = 0.951$ ($P = 0.001$). These results suggest that high RR of bare soils should be avoided as much as possible near or at crop planting to minimize crusting and seedling emergence problems if major rainstorms occur after planting. Although results undoubtedly would be different on other soils, relatively low RR (Table 4) and CS (Table 7) were achieved on the Pullman soil near or at planting time by performing major tillage early in the fallow period. This provided adequate time for natural weathering and subsequent tillage to provide more favorable conditions for seedling emergence when the crop was planted.

Based on multiple linear regression analyses, precipitation was the only factor significantly affecting surface RR (Table 5). This contradicts the results of the analysis of variance. The reason for this contradiction is not known, but is probably related to the limitations of multiple regression analysis. Besides, the coefficient of correlation for the regression (Table 5), although significant, was low, which suggests that other factors had an effect on RR.

### Seedling Emergence

Although rainstorms sometimes cause sorghum emergence problems on Pullman soils, soil crusts resulting from sprinkler irrigations after sorghum planting in 1979 and 1980 did not prevent seedling emergence, probably because the water was applied at a lower intensity than that which occurs during an intense rainstorm. An irrigation was not applied in 1981. Although emergence was not prevented, tillage treatments resulted in significant differences in average seedling counts (Table 9). Final day average seedling counts for tillage treatments were not significantly different. Likewise, neither was the residue level, the residue level × days after planting interaction (data not shown), nor the tillage method × days after planting interaction effect (Table 9) significant. However, the tillage method × residue level interaction effects (data not shown) were significant each year. Although variable from year to year, emergence averaged higher on high than on low residue subplots with MT and DT, little difference with RT and ST, and lower on high than on low residue subplots with NT.

Tillage resulted in variable average seedling counts with no method resulting in consistently low or high average numbers of seedlings. In 1979, MT, DT, and NT resulted in similar counts on each different day after planting. Rotary tillage also resulted in similar counts at 5, 6, and 7 days after planting, but in lower counts at 9 and 13 days. Sweep tillage resulted in lower values than MT, DT, or NT each day, but similar to RT at 9 and 13 days after planting.

In 1980, MT resulted in the lowest number of seedlings each day. Although the counts varied some on different days, DT and NT resulted in a nonsignificant difference in average seedling counts, but the counts were lower than for RT and ST, which had similar counts each day. In 1981, MT and DT resulted in consistently higher seedling counts than RT, ST, or NT each day. The average numbers of seedlings followed the same trend with the differences being statistically significant.

## SUMMARY AND CONCLUSIONS

Moldboard tillage had the greatest effect on measured surface soil physical conditions, with lesser effects resulting from RT, DT, and ST. No-tillage usually had no significant effect. The greatest effect of tillage occurred with the initial operation at the start of fallow. Thereafter, subsequent tillage during fallow minimized differences between tillage treatments. Conditions near or after planting sorghum were similar to those at the start of fallow (after wheat harvest).

Sorghum seedling emergence was not prevented by sprinkler-induced surface crusts, probably due to the low intensity of water application. A major rainstorm, however, caused severe crusting early in one fallow period. Consequently, intense rainstorms after planting could have resulted in emergence problems. Also, different intensity storms would be expected to give different results on other soils and under other climatic and cropping conditions.

Differences in MR, CR of briquette fragments, and surface RR resulting from tillage treatments decreased with time after initial tillage. These factors were associated with soil CS. Therefore, the results suggest that major tillage, when used, should be performed as far in advance of planting as possible to minimize potential plant establishment problems. However, the results of this study also suggest that plant establishment problems can be minimized or avoided by using a conservation tillage system, such as NT. In this study, NT usually resulted in the lowest CS, even after the soil dried following the major rainstorm. The low CS resulted from residues that protected the surface and thereby minimized soil dispersion and reorientation of soil particles, which are associated with soil crusting.

## REFERENCES


1. Allmaras, R.R., R.E. Burwell, W.E. Larson, and R.F. Holt. 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. USDA Conserv. Res. Rep. 7. U.S. Gov't. Printing Office, Washington, DC.
2. Burwell, R.E., and W.E. Larson. 1969. Infiltration as influenced by tillage-induced random roughness and pore space. Soil Sci. Soc. Am. Proc. 33:449–452.
3. Chepil, W.S. 1957. Erosion of soil by wind. p. 308–314. *In* Soil, the 1957 yearbook of agriculture. U.S. Dept. Agric. U.S. Gov't. Printing Office, Washington, DC.
4. Chepil, W.S. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. Soil Sci. Soc. Am. Proc. 26:4–6.
5. Duley, F.L. 1958. Estimating the amount of crop residue on a field. Nebraska Agric. Ext. Stn. Agric. Handbook. 136.
6. Ezekiel, M., and K.A. Fox. 1959. Methods of correlation and regression analysis. 3rd ed. John Wiley & Sons, Inc., New York.
7. Hanks, R.J. 1960. Soil crusting and seedling emergence. Int. Congr. Soil Sci., Trans. 7th. I:340–346.
8. Hudspeth, E.B., and H.M. Taylor. 1961. Factors affecting seedling emergence of Blackwell switchgrass. Agron. J. 53:331–335.
9. Jackson, M.L. 1958. Organic matter determination for soils. Soil chemical analysis. Prentice-Hall, Englewood Cliffs, NJ. pp. 205–226.
10. Johnson, H.P., J.L. Baker, W.D. Schrader, and J.M. Laflen. 1979. Tillage system effects on sediment and nutrients in runoff from small watersheds. Trans. Am. Soc. Agric. Eng. 22:1110–1114.
11. Kemper, W.D., and W.S. Chepil. 1965. Size distribution of aggregates *In* C.A. Black et al. (ed.) Methods of soil analyses, Part 1. Agronomy 9:499–510.
12. LeClerg, E.L., W.H. Leonard, and A.G. Clark. 1962. Field plot technique. 2nd ed. Burgess Publ. Co., Minneapolis, MN.
13. Lyles, L., L.A. Disrud, and R.K. Krauss. 1971. Turbulence intensity as influenced by surface roughness and mean velocity in a wind-tunnel boundary layer. Trans. Am. Soc. Agric. Eng. 14:285–289.
14. Meyer, L.D., W.H. Wischmeier, and G.R. Foster. 1970. Mulch rates required for erosion control on steep slopes. Soil Sci. Soc. Am. Proc. 34:928–931.
15. Parker, J.J., Jr., and H.M. Taylor. 1965. Soil strength and seedling emergence relations. I. Soil type, moisture tension, temperature, and planting depth effects. Agron. J. 57:289–291.
16. Richards, L.A. 1953. Modulus of rupture as an index of crusting of soil. Soil Sci. Soc. Am. Proc. 17:321–323.
17. Taylor, H.M. 1962. Seedling emergence of wheat, grain sorghum, and guar as affected by rigidity and thickness of surface crusts. Soil Sci. Soc. Am. Proc. 26:431–433.
18. Taylor, H.M. G.M. Roberson, and J.J. Parker, Jr. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102:18–22.
19. Unger, P.W. 1969. Physical properties of Pullman silty clay loam as affected by dryland wheat management practices. Texas Agric. Exp. Stn. Misc. Publ. 933.
20. Unger, P.W. 1978. Straw mulch rate effects on soil water storage and sorghum yield. Soil Sci. Soc. Am. J. 42:486–491.
21. Unger, P.W. 1982a. Surface soil physical properties after 36 years of cropping to winter wheat. Soil Sci. Soc. Am. J. 46:796–801.
22. Unger, P.W. 1982b. Effects of tillage method after winter wheat on soil water storage and sorghum yield. Agron. Abstr., Am. Soc. Agron., Madison, WI. p. 258.
23. Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum, and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:885–891.
24. Unger, P.W., R.R. Allen, and A.F. Wiese. 1971. Tillage and herbicides for surface residue maintenance, weed control, and water conservation. J. Soil Water Conserv. 26:147–150.
25. Unger, P.W., and F.B. Pringle. 1981. Pullman soils: Distribution, importance, variability, and management. Texas Agric. Exp. Stn. Bull. B-1372.
26. Unger, P.W., and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. Soil Sci. Soc. Am. J. 43:582–588.
27. Wanjura, D.F. 1973. Effect of physical soil properties on cotton emergence. U.S. Dept. Agric., Agric. Res. Serv. Tech. Bull. 1481. U.S. Gov't Printing Office, Washington, DC.
28. Woodruff, N.P., and F.H. Siddoway. 1973. Wind erosion control. p. 156–162. *In* Conservation tillage. Proc. Nat. Conf., Des Moines, IA, 28–30 March 1973. Soil Conserv. Soc. Am., Ankeny, IA.